SOCIETY FOR THE ENCOURAGEMENT OF ARTS, MANUFACTURES, AND COMMERCE.

CANTOR LECTURES

ON

PHOTOMETRY.

BY

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PHOTOMETRY.

Lecture I.—Delivered April 2, 1894.

The lectures on photometry are not given with the idea that they will be of practical value for the measurement of gas light. There is excellent literature on the subject, part of which I shall have to refer to during my course. What I have undertaken in these lectures is to endeavour to give an idea of the general principles of photometry, almost restricting myself to the scientific aspect of the question. Photometry, in its broadest sense, is the measurement of light, at least, so we must think, from its derivation. Now, the light measured may be light coming from an object, or from a self-luminous body, such as a candle or the sun, or it may be the light transmitted through objects. In the second case, if an appropriate screen be used to receive the light, we are in reality measuring the illuminating power of the source of light, rather than of the light itself. Hence, almost as much depends upon the screen on which the light is received as on the light itself. A screen is usually what is called white, and by white is meant a screen which reflects every colour equally well; but, I would remark that in London the white may become imperceptibly brown, and such colour may interfere materially with accurate results. But the photometry that I am alluding to not only includes the measurement of the illuminating power of light, but the measurement of the light transmitted through bodies of various kinds, when they are transparent, like plain glass, or translucent, like ground glass or paper. The requirements of the candle-power of gas I shall not enter into, as it is a subject which others than myself are much better fitted to deal with.

We may take it, I think, that the first matter we have to consider is the light we have to use as a standard. Parliament, in its wisdom, in 1860, pronounced its standard of light to be the light of a candle 6 candles to the pound, each burning 120 grains of sperm per hour, and this is at present the only legal standard known in England, though why, in the name of common sense, such a definition has been continued our legislators alone can guess, when it has been proved to be so faulty. The standard of light for France is the Carcel lamp, which is equal to about 9·5 candles. Now, a light from a candle is a very pretty thing theoretically, but practically it is anything but practical, as it has the unhappy knack of burning inaccurately, particularly when one is anxious to shield it from draughts. Heat affects the rapidity of combustion, and if it be confined, and no proper access of air be given it, its light may be most irregular. We have to remember that part of the energy of combustion is taken up by melting the sperm, or wax, or whatever it may be, and if the surrounding air be heated the wax is at a temperature nearer its melting point than it should be when at a normal temperature. When the melting point is attained the liquid is decomposed and the flame results, and there is more liquid to be vapourised and vapour to be improperly consumed than in the normal state.

I show you a trace made by photography of the light from a candle burning under normal conditions. The light was admitted through a slit to sensitive paper, and a fresh portion of paper was continually being exposed. You will now see the irregularity of the burning. Of course, by taking several candles the variation is not so great, but even then you have to be sure that the proximity of the candles to one another does not alter the rate of burning.

An Argand burner, however small, will not, during a long series of experiments, differ 1 per cent. in light value. Here we have a proof of this. This small paraffin lamp was allowed to burn for three hours, and you will see that the band it makes is perfectly uniform in appearance, and when the measurement is

made of the blackness produced by it on the photographic paper, it proves my statement is correct.

The apparatus by which these diagrams were made is a very simple one. It consists of a clockwork arrangement drawing a pulley, which pulley is in connection with a drum, which can rotate on its axis. Round this drum is placed sensitive paper, and a box, with a long slit in it, covers the drum. The light is placed opposite the slit, which is covered by a moveable lathe, in which is an aperture of a convenient width. As the drum moves, this aperture moves across the slit, and so we have a corkscrew band of exposure produced. With some clockwork the motion is regular in its irregularity, and every tooth of the train can be counted on it, by noting the bands of varying exposure, and for this reason the clock was at one time abandoned, and the smooth motion of the sinking of the height in subsiding water was substituted. This gave very good results, but for my purpose the clockwork was sufficient.

The sources of light I have mentioned are what may be called feeble sources of light, and cannot be used when a body is fairly absorptive, if the transmitted light is to be measured. We want in such a case a stronger source of light, and one which is practically constant. Such a source of light we have in the electric arc light. If we project upon the screen an image of the points where the positive pole is slightly behind the negative pole, with a fairly long arc, we become aware that there is a central part, which is higher than any other [shown]. It comes from a depression in the positive pole, and for the last eight years I have been in the habit of using this as a source of light of uniform intensity, and many hundreds of measures have proved it to be so. This, as several years ago I pointed out, was due to the fact that the temperature of this spot was that of the volatilisation of carbon. It is an intense light, and may be taken as 50,000 A.L. per inch of surface, and very useful for a great many purposes, as we shall see as we proceed. Now we call all these lights which I have mentioned white, but it is quite evident that there is white and white if all these be white. I believe myself that Mr. Lovibond's definition of white is a good one, which is the light which is seen in a white fog about midday, and if we compare this light with any other we shall, I think, come back to it as being a very practical white light. Now the electric light is not far from this quality of light, and as such is very useful in comparing the transparency of objects by what is approximately daylight. We can measure the light of each part of the crater passing through a small hole.

We can at once see the difference between all the ordinary lights by a simple experiment. This box is divided into partitions with tissue in front, and in each partition we have a different source of light — a partial gas jet, an Argand gas-burner, a candle, and a paraffin lamp. It will be noticed that the light enclosed in a chimney is much whiter than those burned in free air, but you will also see that all these lights have various depths of yellowness when compared with the electric light. It is quite evident that even supposing they gave the same illumination, that they are not all fit for standard lights. I take it that a standard light in photometry must always have the same quality of light as well as the same quantity of light. Now we can, by appropriate means, make the electric glow-lamp light of the same visual intervals as a gas jet. The one before us is so, but it is evidently not of the same quality. One of the very best tests that we can make of ascertaining whether any difference in quality exists is to see if, when they are equally strong visually, they give the same photographic results. [An experiment was made with an electric light and an amyl acetate lamp, in which both were made of the same visual intensity, but photographically they differed materially.] You see that the amyl acetate lamp is decidedly the worse photographically.

Perhaps I can show you why this is. I take an incandescent lamp, and cause it to glow: it goes red, to begin with; then I increase the current, it gets yellow, then whiter, and so on, till it is nearly white. I cannot make it as white as the arc light, for the reason that, as the temperature increases, the fusing point of carbon is reached, and that, as I pointed out, is the temperature of the crater of the arc light. These temperatures, however, are subject to different amounts of energy expended upon them; and here I have a diagram, showing how, with an increased energy expenditure on the same filament—that is, with an increased temperature—the different rays of the spectrum are altered in proportion. These diagrams are taken from measures made with a linear thermopile, moved through the spectrum. You will see that the higher the temperature, much more rapidly do the rays of high refrangibility increase.

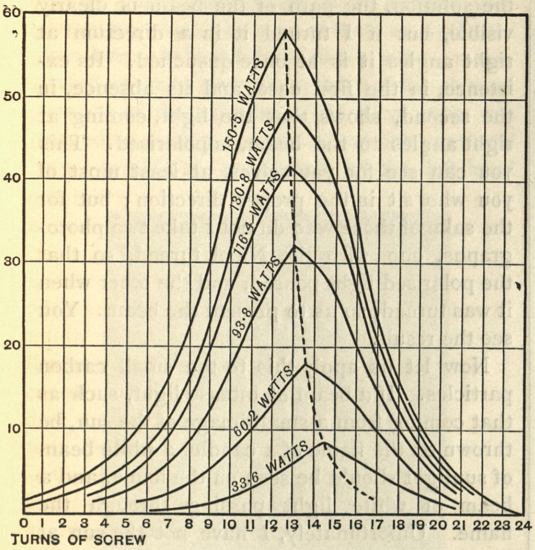


FIG. 1.

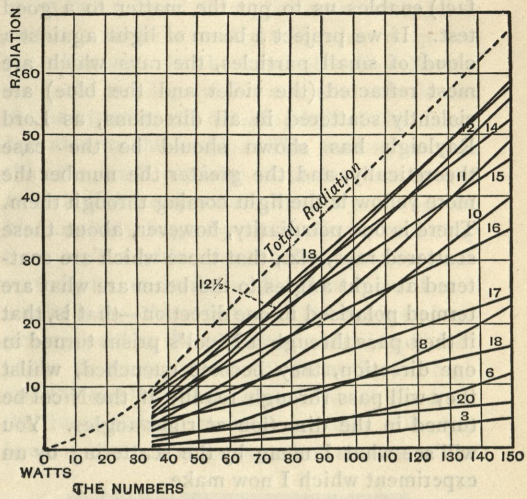


FIG. 2.

The value of the abscissæ in Fig. 1 (in wave lengths) is as follows :—

	λ		λ
1·25	5,900	13	14,650
5	7,250	17	20,750
9	9,900	21	27,500

These numbers apply to both diagrams, and in Fig. 2 the numbers attached to the different curves, are those which are attached to the abscissæ in Fig. 1.

Let me show an experiment. I will balance an electric light against the amyl acetate lamp, and expose a piece of paper to its action. I will increase the temperature and balance again, and expose another portion of the same paper to its influence for the same time. Notice, please, the difference in the two. You will find that the highest temperature filament is much more "photographic." By this means all lights, which are due to the incandescence of solid particles of carbon, can be tested as to quality. Make them visually equal, and then see if they are photographically equal. For my own part, I believe that a knowledge of the photographic value of light is essential in the near future; for I cannot help thinking that there will have to be a registration of photometric values for record, independent of the eye, and this must be by photography.

For this purpose the photographic value, and the visual value of every light used, will have to be known and carefully recorded. We shall see soon how these records can be utilised, and become of permanent value in themselves, being capable of being measured at any date after being made, and re-measured if required. I throw on the screen the photographic values of a candle, an amyl acetate lamp, a gas jet, a paraffin lamp, and an arc light—all made of the same value as a candle visually [shown]. You will see that they vary enormously, and the scale of opacity below, which was made by exposing different parts of a plate to a steady light for different times, gives us a means of comparing one with the other.

I have said that all lights which are due to solid particles of incandescent carbon can be tested by means of photography, and I have shown you the deposits which certain lights cause on a photographic plate. There can now be but little doubt that a luminous candle flame is as much due to solid incandescent particles as the glow-lamp we have been using. The final proof has been long in abeyance, but I think no doubt now can exist regarding it. First of all, if we examine the spectrum of the luminous part of the flame, we find that it is continuous, though occasionally a bright line of sodium in the orange puts in an appearance, but it is of no account. Now any light which emits a continuous spectrum must be due to a solid or liquid body in a state of incandescence, or to a gas in similar state, but under great pressure. The flame is certainly not liquid, nor is it gaseous under pressure. It seems, therefore, the light must be due to solids, and those solids must be so small

that even a microscope of low power will fail to distinguish them. This fact (if it be a fact) enables us to put the matter to a good test. If we project a beam of light against a cloud of small particles, the rays which are most refracted (the violet and the blue) are violently scattered in all directions, as Lord Rayleigh has shown should be the case theoretically, and the greater the number the more yellow is the light coming through them. There is one peculiarity, however, about these scattered rays, viz., that those which are scattered at right angles to the beam are what are termed polarised in one direction—that is, that if they pass through a Nicol's prism turned in one direction, they become quenched, whilst they will pass through readily if the Nicol be turned in the direction at right angles. You will see what I mean by the scattering by an experiment which I now make.

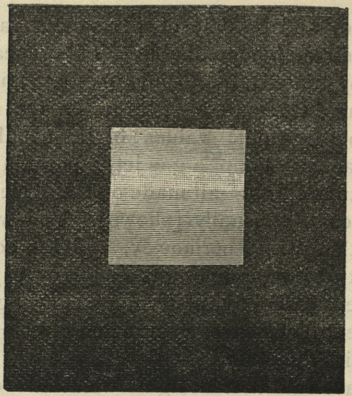


FIG. 3.

If to this clear solution of hyposulphite I add a few drops of hydrochloric acid, it becomes cloudy, owing to precipitation of fine particles of sulphur. I allow a beam of light to pass through the solution before I make the addition to the screen, and then add the HCl. The light becomes yellowish and then reddish, as the number of fine particles increase; that is, the more particles the redder it becomes, and the more light is scattered, as a look at the cell testifies.

By precipitating mastic in water we get the same results. Here is some which has stood two years or more, and while it is turbid the beam of light passes freely through it, but scatters light on each side. Now, if I pass that broad beam of light first through a Nicol's prism, turned in one direction, and then through the solution, the path of the beam is clearly visible, but if I turned it in a direction at right angles it is at once quenched. Its existence, in the first case, and its absence, in the second, shows that the light, coming at right angles to the beam, is polarised. This you can see for yourselves, at least most of you who sit in the proper direction; but for the sake of those who do not I take two photographs, one with the Nicol turned, so that the polarised light passed, and the other when it was turned, so as to present the beam. You see the result.

Now let us apply this to the small carbon particles. If a beam of intense light, such as that coming from a small image of the sun, be thrown on the flame of a candle, a white beam of sunlight should be seen on the flame, and a beam of white light passing through the flame. Unfortunately, I have not the sun at

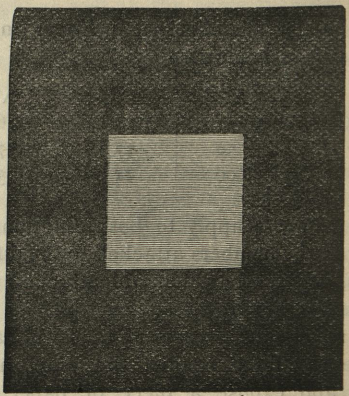


FIG. 4.

my command here to-night, so I cannot show it, but you may take my word for it that such is so. Sir G. Stokes examined this white beam in a position at right angles to its direction, and found, by means of a Nicol's prism, that it was completely polarised; that is, that when the Nicol was turned in one direction, the streak of white light in the flame disappeared altogether. This establishes the fact that the luminous part of the flame is due to small particles, independently of any other proof. It appears to me, therefore, that one is correct in stating that the bright flames are due to measurement carbon. Into the theory of flames I will not further enter at the present time; this is enough for my purpose.

In case there be any doubt amongst you, I will show you some photographs of the phenomena I have taken.

Fig. 5 is a photograph of an Argand gas-flame, on which the rays of the sun, collected by a lens of about 8-inch focus, were concentrated so as to pass along part of the circumference of the cylinder. The Nicol prism was turned in such a direction that the scattered rays would be unaffected in the left-hand

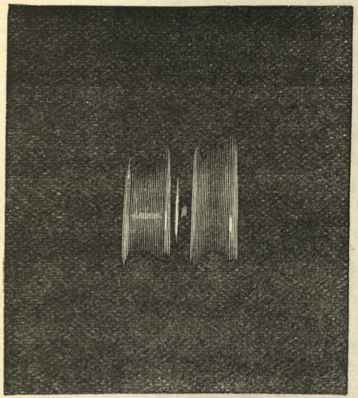


FIG. 5.

photograph, whilst it was turned at right angles to the first direction for the right-hand photograph. In the left-hand figure the track of the beam is readily seen, whereas any trace of it is absent in the right-hand figure. Fig. 6 is the same, but the electric arc light was used in place of the sun. The results are the same.

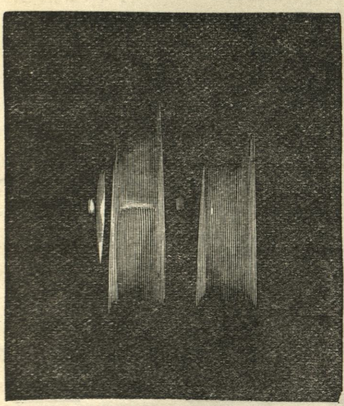


FIG. 6.

Fig. 7 shows the results when the beam from the electric light is passed through a candle flame. In the one figure a broadish white band is seen, whilst in the other it is absent.

We are now in a position to see why it is some flames are whiter than others. When a chimney is used with gas, for instance, we find that the illumination is whiter—bluer, if you like the word better. The function of a chimney is to supply air to the flame, ample room being found through interstices to allow as much air as is needed to be drawn up into the chimney. In the case of hollow flames, such as an Argand burner, not only is the air admitted to the outside shell of the flame, but also to the inside. The consequence is that the small particles of carbon are heated to a higher temperature, as they are in the blacksmith's forge by the bellows, and they then emit a whiter heat before they are converted into carbonic acid. When one has a smoky lamp, there is one of two things happening—either the supply of air is insufficient to the chimney, or else the flame is too high and the sudden access of cold air chills down the incandescent carbon particles till they become black, and smoke results. One of the

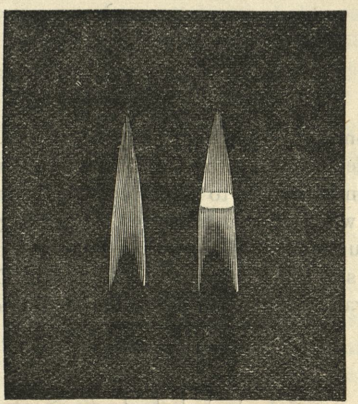


FIG. 7.

most instructive experiments as to the need of air and warmed air to a flame is shown by lighting a paraffin lamp. It is an orange smoky flame, but directly you place the chimney on it the light whitens and the smoke ceases.

I should here like to correct a very common notion which exists regarding the blackening of ceilings by gas flames. As a matter of fact, the carbon in a gas flame ordinarily is totally converted into carbonic acid. It is the ascending current of heated air that catches up the floating motes in the room and dashes them against the ceiling, to which some cling tenaciously, and gradually the blackening is encountered. A friend of mine lately put up the electric light in his house, and placed the glow-lamps close to his ceiling. He was astonished to find that the ceiling above them blackened to an extent which reminded him of gas. It was the current of warm air which

caused the blackening. Similarly, hot-water pipes will do exactly the same thing. Heated air will ascend, and when it ascends it carries the motes and particles with them. In South Kensington Museum, ceilings which adjoin hot-water pipes blacken quicker than where there is gas, the reason being that the volume of heated air is so large.

Lecture II.—Delivered April 9, 1894.

I omitted, from want of space, to say in my last lecture that the fact that a flame viewed end on is from 10 to 35 per cent. less luminous than when viewed sideways. Fig. 8 gives a measurement if taken with a flame at different angles to the screen according to Mr. Dibdin. The variations in the light of a burning candle

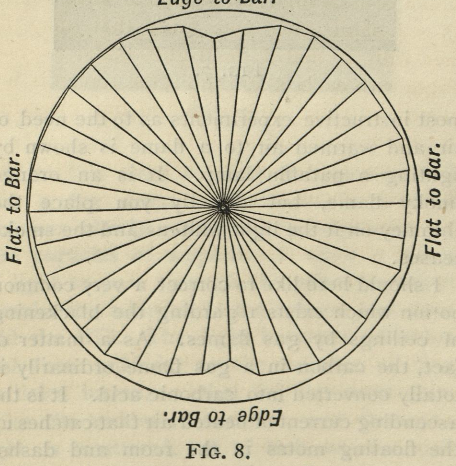


Fig. 8.

has been shown you, and I think that for scientific working it must be dismissed as unworthy of serious consideration. There are only three what I may call feeble light standards which I shall refer to, viz., the amylacetate lamp, due to Hefner Alteneck; the pentane illuminant, and the ether illuminant. I put the amylacetate lamp first not because of its superiority, but because it requires such little manipulation. This is a lamp which is a great favourite of mine because it is so accordant in its results. It consists of a tube of German silver, 8 mm. in diameter, and 25 mm. high. The flame is 40 millimetres high, and when it has been burnt

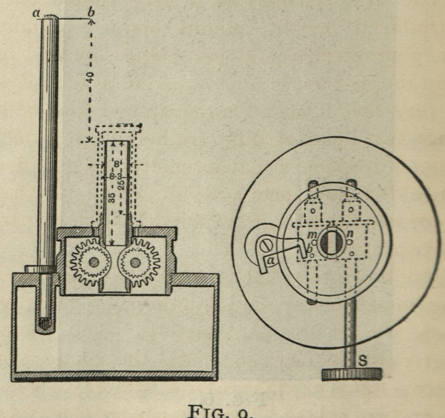


Fig. 9.

for five minutes the flame remains of a constant height. It burns amylacetate, but it is not necessary to use this compound, as any similar one will consume as well. Hefner Alteneck gives a Table of the results of the different compounds and their comparative luminosities :—

	Constitution.	Per cent. of carbon.	Boiling point.	Intensity of light.	Time for the combustion of 1 gramme of the substance	Carbon consumed in 100 seconds.
			C.			
Valerate of Amyl	$C_{10}H_{20}O_2$	69·7	195°	1·03	430	0·162
Acetate of Amyl	$C_7H_{14}O_2$	64 6	138°	1 00	388	0·166
Formiate of Amyl...............	$C_6H_{12}O_2$	62·1	122°	1·01	372	0·163
Acetate of Isobutyl	$C_6H_{12}O_2$	62·1	116°	0·99	373	0·163
Formiate of Isobutyl	$C_5H_{10}O_2$	58·8	98°	0·97	355	0·166

The drawback to this lamp, as originally constructed, is that the metal takes a green deposit, which is tiresome; if it be plated with silver, this disappears.

Dibdin's pentane Argand, which burns pentane, is the next one to refer to, and is the lamp which appears to me most perfectly to utilise the pentane, employed as an illuminant, in a simple method. Pentane is a hydrocarbon of the paraffin series, but is not perfectly pure at all times. The illuminant is air passed over a carburetter containing the pentane. The height of the flame is 3 inches, $\frac{7}{10}$ths of which are cut off by a screen at the top. By these means a standard flame is obtained, which is equal to 10 candles. The great point in this is that the height of the flame does not affect the result, at least it does not to the eye. Temperature has no effect on the result, as Mr. Dibdin has thoroughly tried.

The next standard is a very simple one, introduced by Mr. Dibdin more especially for photographic purposes; ether, instead of pentane, is burnt in a pentane lamp, and gives a very fine light. Photographs taken with hese two lights at different heights of flame, but of the same visual intensity, do not give quite the same photographic effect, so that there is a deviation from the definition of perfect standard.

We have seen what kind of a light we must use for photometry as to quality and quantity. Now we come to photometers. The photometry we will first consider is the comparison of two lights together. How are we to compare two lights? There is one evident way, and that is to place side by side two white surfaces which are illuminated by the two lights. This is the principle of Rumford's photometer and nothing else. We are usually told that it is the method of shadows—the comparison of shadows one with the other. Now it is nothing of the kind, it is really the illumination of a surface by two distinct lights, the one illumination being not interfered with by the other, and this is secured by making one light cast a shadow of a rod on the screen, which is illuminated by the other, and this last light to cast a shadow of the same rod at a different place, which is illuminated by the first light. These two illuminated surfaces can be made to touch by moving the rod or the angle of the light, and by various plans these can be equalised in brightness. No less a distinguished authority on photometry than Mr. Dibdin, in an excellent book he has written, says, although this method has certain advantages, "the method is one which few practical photometrists of the present day would venture to adopt." Well, I am a tolerably practical photometrist myself, and I must confess I prefer it to any other kind of photometry, as it is simple, and very few errors can creep in if one is ordinarily careful, which is more than can be said of some others, as we shall see. One error that may be met with is that if the lights make a great angle with each other, and if the screen is not placed at right angles to the line bisecting the angle, an error may creep in.

Let me show you this experimentally, and this experiment really demonstrates another mode of photometry.

This white cube is placed between two lights, one of the right angles of the cube being towards you. I place a square aperture in front, so that it is bisected by the edge. The cube is rotated round that edge as a centre, till the two sides appear equally illuminated. The reason of the equality of illumination is quite plain. It is because the side nearest the light is skewed at a greater angle than the other to it. If we have a diagram, we shall see why this is. In Fig. 10 (p. 8) A B and B A are the two sides of the cube illuminated by rays R and R. It is evident that the side A B will not receive so many rays as B C, in fact, the amounts are measured by pq and mn. If the lights are unequal, of course when the

intensity of the one multiplied by pq is equal to the intensity of the other multiplied by mn the two will equal. The intensities, where a balance is struck, is found by taking the cosines of the angles through which the cube is turned.

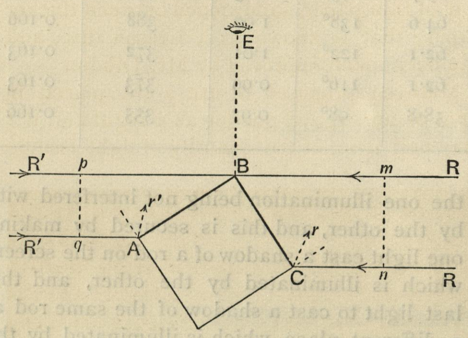


FIG. 10.

We now see that light illuminating a surface varies as the cosine of the angle through which it is turned. If it be turned 5° more towards one light than the other it is evident that we shall get a variation. The amount would be as 1 to ·996, or an error of $\frac{4}{1000}$, or $\frac{1}{250}$. If it were 10° it would be 1 to ·984, or $\frac{16}{8000}$ or $\frac{1}{82}$ part, which would be appreciable.

There is still one more error which might be felt, and that is that the eye receives more light when the angle which the screen makes with the eye and the source of light is greater than a right angle (see r and r' in Fig. 10). This must always be the case, but what may be called the difference in the specular reflection is so small for ordinary angles, that it is of the same order as that given for the wrong placing of the screen, and becomes practically negligible.

For great accuracy the illuminated shadows should touch, and if the lights be not too broad, there is no difficulty in causing this to be done; sometimes, however, a white line or a black line will separate the two owing to the penumbra of the shadows, and then making the illuminations of the two strips equal becomes more difficult. As the black line has greater contrast to the two illumined surfaces than the white line has; the former is the worst kind of line to put up with.

The next method that is adopted is what is known as the Bunsen method. It consists of equalising the brightness of a greased spot in the centre of a paper disc, or its total disappearance. The principle on which this is based is the translucence of the spot. If as much light goes through the spot (if perfectly made) from one light as goes through from the other, the spot is equally illuminated throughout its thickness, and appears the same whiteness as the paper. If it be greater on one side it will appear dark on one side, and lighter on the other. It is evident that with such a method every suspicion of stray light must be rigidly excluded, unless it be exactly the same on both sides of the disc, and only that coming directly from the sources of light utilised. Light reflected from the sides or bars will give fatal results as far as accuracy is concerned. I have met with some instruments in which reflections seem to have been encouraged rather than allayed. To my mind the method should not be accepted except in the hands of those who are thoroughly practical and scientific. I show the design of a Letheby photometer, kindly lent me by Mr. Sugg. [The instrument itself was in the lecture-room, through Mr. Sugg's goodwill.] The grease spot is viewed on both sides by inclined mirrors, and when the grease spot disappears on both sides, or at all events appears to equally dim on each side, the light illuminating the spot may be said to be equal.

There is one thing to be noted, and that is that very much depends upon the kind and amount of grease, and the kind of paper, employed. I have made a good many grease spots in my day, and I have found the sensitiveness of the method vary considerably according to the attention paid to these details, but I have abandoned the method in my laboratory, except under special circumstances, in favour of the old Rumford method.

Mr. Dibdin, in his work, says:—

"When first setting up a disc for use, special experimental readings should be taken; and if any material difference is found between the indications when one side or the other is turned towards the standard flame, it should unhesitatingly be rejected, as no amount of after allowance can compensate for the trouble and doubt arising from contradictory results. The disc should be clean and perfectly free from scratches or other markings of any kind; it is but sorry economy to work with a defective instrument. The Gas Referees went so far, a short time back, as to run a new disc, to be used every week. As, however, a good disc, when taken care of, will last much longer than that period, the point has not been insisted upon; but that is no excuse for the continued use of a defective one, which should be instantly destroyed as soon as detected."

We see from this that a disc photometer is open to a very grave objection, and it is for this, if for no other reason, that I prefer the

Rumford system, where there is no liability to err on this matter. A modification of the Rumford method of shadows is that employed by Prof. V. Harcourt. He casts his shadows on ordinary printing paper, rendered partially translucent by a wash of spermacetti dissolved in petroleum. Instead of a rod, and about three-quarters of an inch from the paper, he places a brass screen, having two rectangular apertures cut in it exactly their own breadth apart. The two lights are placed at equal angles on each side of the line perpendicular to the screen, and the illuminated shadows are caused to just touch one another. It will be noticed

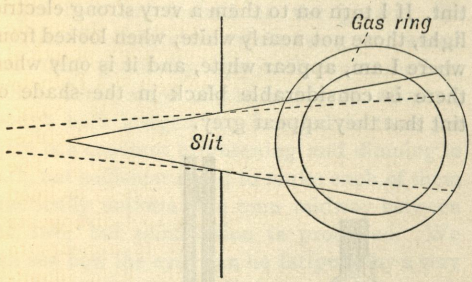


FIG. 11.

that really there are four shadows illuminated, one from one light being touched by the other two, and the fourth falling on an opaque or black space. A great advantage of this plan is that they are looked at from the back of the screen, no rod being between the eye and the screen. If two lights of approximately the same colour are looked at, the fact that the light has to traverse the paper is of no moment, though, when coloured lights have to be compressed, there is a danger of absorption slightly altering the values that should be obtained.

Before quitting the subject of the Bunsen method, I ought to mention that in photometry, for the grease spot is sometimes substituted a star of thin paper, sandwiched between thicker paper; that is known as a Leeson disc, and has been much improved by Mr. Dibdin.

Methven proposed to use a slit placed in front of an Argand gas-jet as a regulator, if I may call it so, of the quantity of light issuing

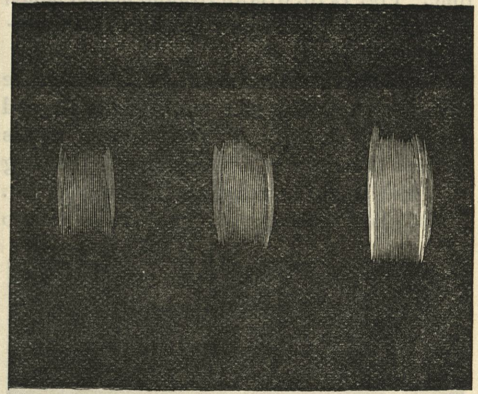


FIG. 12.

on to the grease spot. This appears at first sight an admirable arrangement, and it would answer well if the grease spot were always kept at the same distance from the source of light, but when it is moved, an error, though it may be very small, must be introduced. An Argand flame is practically a hollow cylinder of light, of a certain thickness (Fig. 11). As you approach the light the section of the cylinder varies,

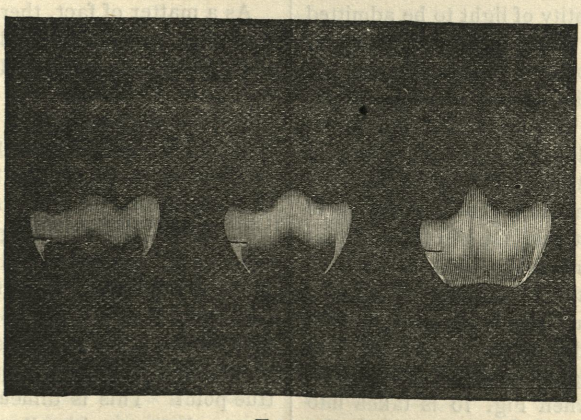


FIG. 13.

and consequently the quantity of light falling on the spot must vary beyond what it should do. It may be remarked that putting aside this error the measurements are made from the slit and not from the source of light, which is a decided advantage. Messrs. Hurter and

Driffield have to a large extent got rid of this light and employ a flat flame, of large size, as the source of light, and use a small square aperture in front of the flat side. As the section of such a flame appears to be uniform, the inaccuracy of measurement introduced is done away with. In reference to this, it may be interesting to show that in an ordinary flame the light varies in intensity at different points. This can be done well by means of photography, reducing the exposure each time. Fig. 12 (p. 9) is an Argand burner flame, Fig. 13 (p. 9) a batswing, and Fig. 14 an ordinary candle.

It will be seen that in the candle flame we have an almost expected result. The Argand gas is more surprising. The batswing gas is perhaps the best, as it shows that in the wing used the intensity remains almost constant. I think these photographs will demonstrate to

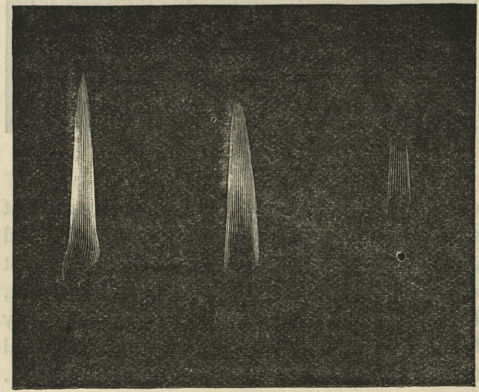


FIG. 14.

you that if the quantity of light to be admitted to a screen is to be determined by an aperture, the burner should be of the batswing type.

Before quitting the subject of photometers, I must introduce to your notice the radial photometer of Dibdin (Fig. 15). The diagram almost explains itself. The object of the photometer is to measure the illumination of a flame in all directions. It will be seen that the arm which carries the light to be tried remains always at the same distance from the screen. The screen itself is so arranged that its surface bisects the angles between the lines joining the two lights and itself — a most necessary thing, when Fig. 10 is taken into consideration.

We have now to turn to the method of judging the equality of light; that is, how the eye can best appreciate the light.

We are told very frequently that the eye can appreciate about the $\frac{1}{60}$th part in the intensity of light, or, say, 2 per cent. There is a story told of a celebrated witness who, when asked whether such and such a thing was the case, said :—" Yes and No." Now if I were asked the question as to whether the above limit was true, I could safely answer in the same terms. First of all let me show you an experiment, which will prove that this limit is both understated and also overstated. I have on this screen a variety of greys between black and white. We can now see them all, and the difference between them. If I turn down the light, a great many of these appear the same tint. If I turn on to them a very strong electric light, those not nearly white, when looked from where I am, appear white, and it is only when there is considerable black in the shade of tint that they appear grey.

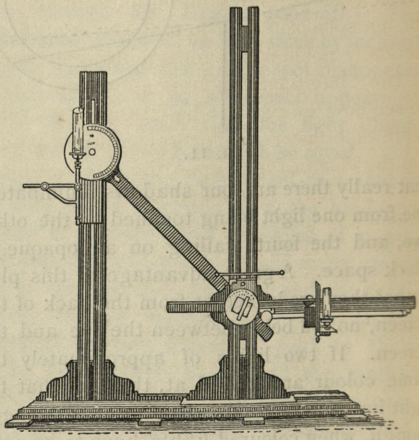


FIG. 15.

As a matter of fact, there is an intensity of light, in which much smaller differences than the $\frac{1}{60}$th can be perceived. I believe, for my own part, that, when the light is suitable, a difference of nearly $\frac{1}{200}$ is recognisable. But it is not necessary that the eye should be so sensitive as the above, so long as proper precautions are taken in balancing the light. If we balance from "too light" and then from "too dark," the mean will be fairly exact, and probably not be far off the truth by a good deal less than 1 per cent. But there is another plan, which is better still, and that is by rapid oscillations in intensity on each side of the true point. This is difficult with many photometers, but not with all. When this plan is adopted, supposing we are using the shadow method, the two shadows appear to *wink*, and, when exactly balanced, this winking stops. It is curious how, without this artifice, readings

which can be proved to be palpably wrong, are made. For instance, when one shadow is intensely darker than another, the eye of the observer will fail to see it, when the alteration is made slowly. If the eye, however, has a rest, by looking away at some black object, the inequality of the shadows will at once be seen. This cannot happen when the method of rapid oscillation is adopted.

What the cause of this may be is not absolutely proved. When the eyes look at two objects (spots or shadows) the images of the two are projected on different parts of the eye, these portions get fatigued, and the longer they are looked at the greater the fatigue. The brightness of the two gets lowered and they gradually approach one another. When the system of oscillation is adopted, though both images are lowered in tone, yet there is a constant brightening and dimning in both, not sufficient rapid to make each of them practically uniform in a tone midway between the two, but scintillation is produced. We can see how the eyes can be fatigued by a very simple experiment. I will throw a bright patch from the electric light upon the screen, which is also partially illuminated by gas-light. If the audience look at it for a few seconds, and keep their eyes fixed on the screen when I cut off the electric light, they will see a dark spot where the bright patch was, and it will appear to travel about as the eye wanders over the screen. This shows that the part of the retina on which the white patch was received is fatigued, and is less sensitive to the feeble gas-light illumination with which the screen is illuminated.

Some very instructive measures of the sensitiveness of the eye to different shades of light can be made by a sector arrangement. Black dots of any size required (in the case in point they have one-eighth of an inch in diameter) can be placed on a white disc, as shown. This disc is cut radially from the centre, and a black disc is marked out in the figure. The proportion of black and white can be altered at pleasure, and a further slight alteration in the grey produced is made by the dots; the

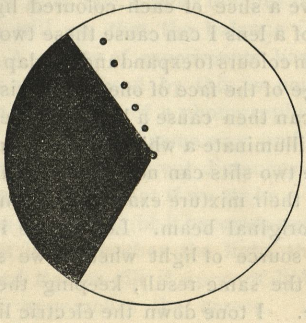


FIG. 16.

smallest alteration, of course, being when the dot subtends the smallest angle. By this plan the sensitiveness of the eye to any small change in light can at once be found. The sector may be varied between all white to nearly all black. Similarly white dots may be placed on a black disc, a white disc overlapping, and unique measures made. It must be remembered that in all cases the black itself reflects a certain amount (in this case about 4 per cent.) of white light.

Lecture III.—Delivered April 16, 1894.

The sensitiveness of the eye to changes in intensity, I have shown you, varies according to the intensity of light from which the variation takes place. As my time is short, I must omit some other theoretical considerations which it was my intention to show you. I will first of all commence by showing how it can be ascertained whether a light is up to the standard temperature, such standard temperature being required for visual and photographic comparisons.

It is well known that by mixing two properly chosen spectrum colours white light can be formed, and when I say white light, I mean the

colour of the light under trial. Now, for lecture purposes, it is useless for me to try and use the light of a candle to form a spectrum. It would be invisible to you all; but I can use the electric light just as well for the object I have in view, viz., the demonstration of the principles involved. Now the whiter the light, the more blue and violet there is in its spectrum. There is, therefore, a large quantity of blue and violet in the electric light. I will form a spectrum, and place a slit in the orange and another slit in the blue, so that I can have a slice of each coloured light. By means of a lens I can cause these two slices of spectrum colours to expand and overlap and form an image of the face of one of the prisms used, and I can then cause a beam of the original light to illuminate a white surface alongside of it. The two slits can now be opened till they form by their mixture exactly the same colour as the original beam. Let us see if we use another source of light whether we shall get exactly the same result, keeping the slits as they are. I tone down the electric light by a very pale yellow glass: the light imitates very closely gas-light. If we place it in front of the slit of the spectroscope, so that the spectrum is the spectrum of the yellower light, and the incident beam is the yellow light, you will see at once that the mixture of the two colours no longer gives the same colour as the yellow light. Making the light the same as the amylacetate lamp light, you will see again that the balance is upset, the two patches of light on the two white surfaces are no longer the same.

Here, then, we have an indication of the method to pursue in ascertaining if lights are of the same quality. By having two adjustable slits in the spectrum, which will with a standard light exactly match the colour of such a standard, we can at once see if any other light is of the same value; if it is not, the two illuminated surfaces will be of a different hue. Another plan is to use proper coloured glasses in front of a lens, and allow light to pass through them in such proportions that they cast an image of a beam of exactly the same colour as that of the standard light itself. When another light is used, equality of colour no longer exists.

There is one method of altering the intensity of a light, if it be a glow-lamp which may interest some. In the first lecture I showed how the visible rays increase in intensity in a parabolic curve. This was further investigated by General Festing and myself. If each ray goes up parabolically, it is probable that the sum of them does the same. In a paper read at the Royal Society on December 8, 1887, we showed that our surmise was correct, and that if a constant was deducted from the current multiplied by the volts the result was the square root of the light multiplied by a constant—($w - m = n\sqrt{y}$,) which is a parabolic. By altering the resistance in the lamp, and reading an amperemeter, and a voltmeter, the result is obtained, though it is sufficient if the amperes alone be read, for then $c^2 - s = t\sqrt{y}$, very nearly when c is current and y the light, s and t being constants.

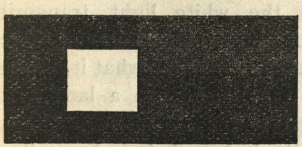
As to the use of the sectors, it has been brought to my notice that Mr. Ferry has called in question the accuracy of the sectors when comparing lights of different colours with one another, such as lime-light and a glow-lamp. He states that for light of the same colour, and for monochromatic light, no error can be found in its use. I may refer, however, in opposition to this, to some experiments which were carried out by General Festing and myself, in which the luminosity of the spectrum was measured without the intervention of the sectors, comparison having been made with a glow-lamp. It was found, as published, that the two methods gave identical results. There are many other experiments which show that no error in the results obtained with the sector have been found by us. That this is the case, we may take to be the fact by direct and by indirect measures.

There is, in my opinion, no method so good in photometry as that of using properly moving rotating sectors, whose open apertures can be altered at will. It allows both lights to remain stationary, as, also, the screen. This method of diminishing the intensity of the light was, I believe, first introduced by Fox Talbot more than fifty years ago, though he had not the advantage of using moveable apertures. This principle of altering the aperture during rotation I first saw exhibited by Mr. Kempe, Q.C., at a *soirée* of the Royal Society. It was applied to a colour top. Without entering into the history of the matter, however, let me show you the exactitude with which such sectors can be employed.

In doing this, I wish to introduce to your notice a photometric method which I brought out, and is, I believe, very fairly successful. I am not saying it is the very best for comparing ordinary lights, but it fills a gap for measuring light transmitted through

bodies, which is very convenient. The principle of the screen, you will at once see, is different from almost any other. It consists of a square aperture cut in a thin disc, and over this is stretched a white piece of paper of such a nature that the light from an illuminant is only scattered, and no direct image can be seen under any circumstances. On the other side is cut a mark in black paper or black retint, which is exactly double the size of the cut-out square, and this is filled up by the white paper stretched over the aperture, so

FIG. 17.



Back View.

that we have a rectangle of paper half of which is translucent and the other half opaque. If now we place a light behind the aperture, the half is illuminated by transmitted light, and if a light is placed on the other side, the whole rectangle is illuminated. By placing a rod in the path of this last beam, we may cast a shadow which prevents the last illuminating the half through which the transmitted beam comes, and then we have half the paper rectangle illuminated by transmitted light, and the other half by incident light. If the paper be of good quality, the light will

Front View.

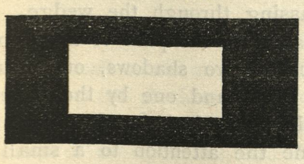


FIG. 18.

appear of the same colour. By placing the rotating sectors in the path of the front beam, and altering the apertures, we may cause the two to appear of equal brightness.

Now suppose I want to examine the amount of light transmitted through this piece of ground glass, I can readily do it. If I place it near the candle, and use an ordinary Bunsen or Rumford photometer, I shall find that it varies according as I place it close to the source of light, or half way, or close to the screen. It is quite evident that the closer I place it to the screen, the truer will be the measure of the total amount of light transmitted. With this photometer I can get the ground glass close to the screen, and we then get a measure of the transmission of light through it. An objection has been made that light has been reflected back from the surface of the white paper to the glass, and back from that surface again. This may be true to a very limited extent. If I take a piece of ordinary glass, and hold it close to the lamp, I can balance the two lights, bringing it closer and closer, till it in fact almost touches the aperture, you will see that the balance is undisturbed. A variety of experiments has shown that any error caused by this is negligible. We can take a piece of a photographic negative, and test it in the same way, and balance it, and move it at different distances towards the screen ; we find that if we strike a balance when it is near the light it becomes apparently darker as it approaches the light, then gets lighter and lighter, till it appears lightest of all as it approaches the screen. Another point is this, that it need not be used in a totally dark room, where provision is made that any light there is must pass through the body under measurement; a small amount of diffused light is of no very great moment anywhere, since it illuminates the front of the rectangle, and has no effect on the measures of the light transmitted. We can also use it for coloured objects, such as coloured glass. For ordinary purposes it suffices if the glass be placed against the aperture, or in the path of the beam somewhere, so long as the aperture is only illuminated by the light transmitted through the glass. This makes one half coloured; but it is easy to balance the illuminations by the oscillations of the sector [This was experimentally demonstrated.] The light passed through is then very easily found. Again I may use coloured paper and do the same. To myself it is more easy to balance a coloured light against a white one than a white one against the white. I need scarcely say that, first of all, the illuminations of the white surfaces are balanced, and the sector opening read before the light coming through any coloured or other body is measured. If the white surface require a sector opening of 80°, and only 40° when a body is against the aperture in the screen, half the light is transmitted.

We may often want to know the amount of light reflected from a body, and the next photometer I shall show you is used by me

for that purpose. It is very similar in principle to the last. The aperture is cut as before, but instead of being covered up, it is left open to allow the coloured object to be placed in it, alongside a white square. Instead of two lights one light may be used for this photometer, a reflection being used instead of the second light. This avoids any alteration in the relative intensities of the two lights used, for they both are from the same source. A rod casts shadows, one on the aperture and the other on the white square. The aperture is fitted with (say) a grey square, and the sectors in the direct beam altered till the two appear of the same colour; or I may introduce a coloured object and repeat the process. In this case, of course, first of all the aperture should be fitted with a white surface and a measure taken, and the aperture of the two measures of the sectors gives the relative brightness of the two objects.

There are often cases where we may wish to measure bodies which only allow but very little light to pass, though they are transparent. In such a case we have to use a very powerful light, and it may be that the body varies greatly in absorption at different parts. For this reason I use the electric arc light as the source, and concentrate it so as to give a brilliant beam. There are, however, variations in the electric (arc) light from time to time, and unless the comparison light, with which the relative intensities passing through different parts of the wedge are measured, varies at exactly the same time and in the same proportion, the measurements will often be very much out. If we merely wish to measure the white light transmitted, the apparatus to employ is not very extensive, and Fig. 19 will show what it is. E L is the electric light, placed in a lantern or box of some kind, to prevent the room, which should be slightly darkened, from being flooded with light. L_1 is a condenser which throws an image of the crater of the positive pole upon the slit, S, of the collimator, C. The rays issue

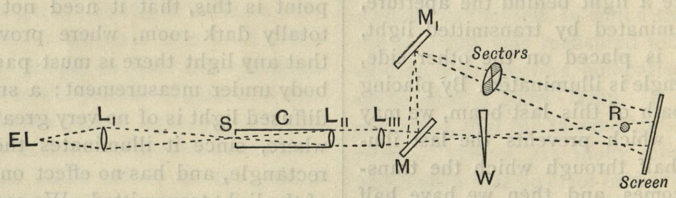


FIG. 19.

parallel, and are caught by a lens L_{III}, which forms an image of the slit upon the surface of the wedge, W, placed in a proper position and in its mountings. The light, after passing through the wedge, forms a circle of light on the screen. It will be noticed that the image of the slit may be as narrow as one wishes by opening or closing S, and that we have a line of light passing through the wedge, such as is required to effect the graduation. Calculation will show that, with a fairly narrow slit, the measured intensity passing through it may be taken as that passing through the mean thickness of that part on which the image falls.

Placed in the path of the beam, and between the wedge and L_{III}, is a plain mirror, M (for which I often substitute a prism of $1\frac{1}{2}°$, and so obtain a single reflection), which reflects the light at right angles, or any convenient angle to its path. It is again reflected from M_1, a silver on glass mirror. An image of the slit is formed in the path, and a second disc is formed on the screen. The centre of this disc is made to coincide with the centre of the disc formed by the light passing through the wedge. A rod, R, is placed in the path of the two beams, which casts two shadows, one illuminated by one beam and one by the other. The usual black mask is used on the screen, to confine the attention to a small part of the shadows.

It will be seen that, when any variation takes place in the light, it equally affects both the illuminated shadows; hence the measures may be made without fear of error creeping in. Sectors with apertures, moving at will whilst they are rotating, are introduced, as shown in the figure, and sometimes a second set of fixed sectors are introduced between M and W should the light passing through W be too bright. The screen is placed perpendicular to the line bisecting the angle made by the two beams. It should be noted that this plan almost necessitates movable sectors, but

sectors which are fixed at known apertures can be used at a pinch, and the balance made by moving the wedge in its settings.

It should be remarked that though the wedge may not be pure black the readings can be very readily made by the method of oscillating between "too light" and "too dark" for the shadow whose brightness is controlled by the sector. In making a valuation of the wedge, the first thing to do is to compare the lights without the intervention of the wedge, and then to take readings.

For certain purposes it is necessary to know how much of each colour of the spectrum is transmitted through a wedge, and Fig. 20 shows how this is accomplished.

The electric light and the collimator are placed as before, but the parallel emergent rays fall upon a pair of prisms, and the spectrum is brought to a focus by L_{11} on to a screen in which there is a slit against which the wedge in its setting is placed. The slit can be placed in any spectrum ray, and the wedge surface is always kept perpendicular to that ray. A lens, L_{111} brings the rays to a focus, so that a monochromatic image of the surface of the last prism is formed on the screen. From the surface of the first prism parallel rays are reflected: these are caught by a mirror and fall on a pair of precisely similar prisms, and the remainder of the apparatus is exactly the same as that described above, a second patch of coloured light being formed over the first patch. The slit, S_{111}, is so adjusted in the spectrum that the two patches are of the same colour. The

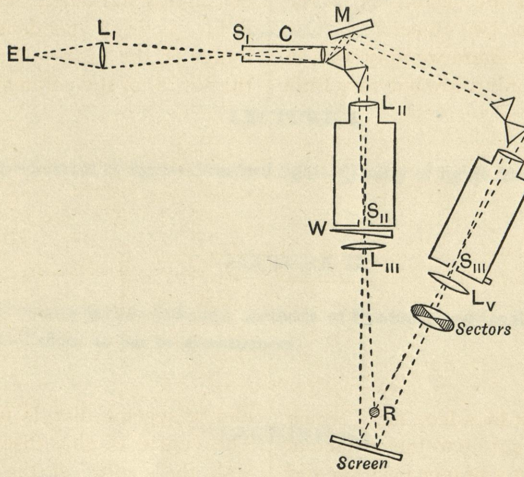


Fig. 20.

sectors are placed as shown in the figure, the rod, R, forming two shadows, as before. The method of procedure is to place the slit, S_{11} in some colour in the spectrum, and S_{111} in the same. The wedge is then graduated for this beam throughout its length, another position is taken up, and the same process gone through. By this means we get the logarithmic factor of transparency for each part of the wedge for the whole of the spectrum colours.

The last point that I shall have to refer to is an apparent failure of the law of inverse squares as regards photometry.

I have upon the screen two patches of spectrum light—a red and a green—of equal intensity, if anything the red is rather the brighter. I place the rotating sectors in front of them and gradually close them. Notice that the red begins to fade away much more rapidly than the green. When very nearly closed the red has disappeared and the green remains not of its light green colour but as a green grey.

Let us argue from this what should result. If when we illuminate a screen with red light we can remove it to such a distance that the screen becomes invisible, though if we have green light, which appeared of equal brightness when close to it, we should be able to remove it much further before the same screen became invisible. The point at which the screen disappeared from view would evidently be the zero point from which the illumination would have to be reckoned for the colour which was used. So with white light, there is a point at which the screen would become invisible.

Evidently then the law of inverse squares for illumination appears to fail for low intenseness of light, and this is owing to the insensitiveness of the eye. Theoretically, of course, the screen may be moved to an infinite distance and still be visible. The law is obeyed practically of course. It may be thought that this limit of vision is of no practical account. But I must say that it is. For instance, in the photographic room we use red light, and we find that the corners of a fairly-sized room are invisible. If we use canary medium the corners will be well illuminated. This is owing to what I may call the superior space penetrating power of illumination of the yellow-greenish light over the red.

I have not been able to show all I wished owing to want of time, but I trust that what I have shown may not be lacking in instructiveness.

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